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Rain Erosion Studies of Sapphire, Aluminum Oxynitride, Spinel, Lanthana-Doped Yttria and TAF Glass

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JULY 1990

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FOREWORD

This report describes work performed between August 1988 and June 1990 to compare the rain erosion resistance of missile-dome materials in simulated rain fields at the University of Dayton Research Institute at Wright-Patterson Air Force Base in Ohio and at the Naval Air Development Center in Warminster, Pa. Visual and microscopic observations of erosion damage are reported and optical scatter measurements made before and after the erosion tests are compared.

Work was carried out in the Optical and Electronic Materials Branch of the Chemistry Division and in the Physical Optics and Thin Films Branch of the Physics Division of the Research Department, as well as in the Technology Advancement Group. The project was funded by the Sidewinder Program Office at the Naval Weapons Center and by the NS2A Weapons and Spacecraft Materials Block of the Office of Naval Technology.

This work has been reviewed for technical accuracy by Ronald A. Marsh.

Approved by
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(U) This report describes the results of testing six potential missile dome materials in simulated rain fields in whirling-arm facilities. Visual damange and changes of optical scatter are described.

14. SUBJECT TERMS
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CONTENTS

SUMMARY

Six potential missile dome materials were tested in simulated rain fields in the whirling-arm facilities at the University of Dayton Research Institute (UDRI, Wright-Patterson Air Force Base, Ohio) and at the Naval Air Development Center (NADC, Warminster, Pa.). Flat plate specimens with a thickness of 5.1 mm were exposed from 5 to 40 minutes at a 90 degree impact angle at a nominal speed of 220 m/s (500 mi/h, Mach 0.64) to 2-mm-diameter raindrops falling at nominal rates of 25 mm/h (Dayton) or 13 mm/h (Warminster). The six materials are single crystal sapphire (aluminum oxide, Crystal Systems, Salem, Mass.), alumihum oxynitride (ALON, Raytheon Research Division, Lexington, Mass.), spinel from two different manufacturers (magnesium aluminum oxide, Raytheon and Coors Porcelain Co., Golden, Colo.), lanthana-doped yttria (yttrium oxide with 9-mole-percent lanthanum oxide, GTE Laboratories, Waltham, Mass.) and Hoya TAF-1 glass. Visual and microscopic observations of samples exposed to the rain field show no damage to ALON and Raytheon spinel and little or no damage to sapphire. Coors spinel, lanthana-doped yttria, and TAF glass suffered significant damage, including pitting and fracture. Total integrated light scatter at wavelengths of 0.647, 1.15, and 3.39 μm showed little or no change as a result of rain field exposure. Most of the surface of most of the samples was undamaged. Only at damage sites is there a change in optical scatter. The materials that survive rain exposure under these conditions have negligible change of optical properties.

INTRODUCTION

The optical seeker at the nose of a missile is protected by a transparent ceramic or glass dome that must withstand the harsh conditions of missile flight. Exposure to rain during captive carry beneath an aircraft wing may damage the dome and limit its service life. This study was conducted to compare rain-erosion damage to several potential dome materials with good visible transmission. The optical scatter of these materials ranges from very low (single-crystal sapphire with 0.03% visible scatter in the forward hemisphere), to moderate (TAF glass with 0.15% visible scatter), to high (Coors spinel with 7% visible scatter). The purpose of the study was to compare mechanical survival of the materials and optical degradation in the rain field.

METHODS

All samples were clear, colorless disks with a thickness of 5.1 mm and diameters of 22.2 mm for rain erosion tests at UDRI and 25.3 mm for tests at NADC. Materials were exposed from 5 to 40 minutes at a 90-degree impact angle at a nominal speed of 220 m/s (500 mi/h, Mach 0.64) to 2-mm-diameter raindrops falling at nominal rates of 25 mm/h (UDRI) or 13 mm/h (NADC). Detailed characteristics of the two rain-erosion test facilities have been described (Reference 1). There are indications that aerodynamic effects can change the effective size of a drop in these facilities. Also mounting effects and centrifugal force during the test could result in damage independent of raindrop impact.

The materials used in this study were single crystal sapphire (aluminum oxide, Al_2O_3, Crystal Systems), aluminum oxynitride (ALON, 9 Al_2O_3·5 AlN, Raytheon), spinel from two different manufacturers (magnesium aluminum oxide, $MgAl_2O_4$, Raytheon and Coors), lanthana-doped yttria (0.91 Y_2O_3·0.09 La_2O_3, GTE Laboratories) and Hoya TAF-1 glass. Some properties taken from the literature are summarized in Table 1. Data for the TAF glass were not available.

Table 2 gives average integrated scatter for the samples used in this study. To make this measurement (Reference 2), laser light is passed through the sample and all light in the forward hemisphere that is diverted into the cone between 2.5 and 70 degrees from the central beam is collected and expressed as a percentage of the incident radiant power. Typically, 20 to 40 measurements were made on each disk and an average value is reported. The standard deviations in parentheses in Table 2 correspond to the variation from the average values for ten samples. The variation within one sample is much smaller. For most of these materials, we do not know what fraction of light is scattered in the back hemisphere. For lanthana-doped yttria, however, the forward/back scatter ratio is approximately 5 at 0.6 µm, 2 at 1 µm, and 1 at 3 µm (Reference 3). The scatter listed for Raytheon ALON (not "High Scatter ALON") is typical of what might be expected for a production material.

VISUAL AND MICROSCOPIC OBSERVATIONS

Table 3 summarizes visual observations of samples exposed to the rain fields. ALON and Raytheon spinel were undamaged, while sapphire suffered some pitting at UDRI. "High scatter" ALON also suffered some pitting, but this is not representative of a production-quality material and we dismissed this result. Coors spinel, lanthana-doped yttria, and TAF glass were extensively damaged.

A number of the eroded specimens were examined with light microscopy at the Naval Weapons Center (NWC). Five of the Coors spinel samples run at NADC were examined by eye and the most damaged one had three obvious nicks in it. Figure 1 is a photograph of the disk at very low magnification; two damage sites are visible. It is noteworthy that the vast majority of the surface of this disk is undamaged. A photomicrograph of the largest flaw in Figure 1 is shown in Figure 2. Figure 3 shows the flaw near the center of the disk in Figure 1. Photographs of Coors spinel and sapphire run at UDRI are shown in Figures 4 through 7. Although the current production-quality ALON from Raytheon was not damaged in the rain field, the high scatter ALON was damaged; a photomicrograph of a flaw is shown in Figure 8. Figures 9 and 10 show two different damage sites on a lanthana-doped yttria disk run at UDRI.

The fracture origins of several lanthana-doped yttria samples were examined. In one case, the fracture origin was found to be on the back face suggesting an unusual stress pattern perhaps related to the method of holding the test specimen. Also edge fractures were noted which probably were caused in the same manner. Upon closer examination of a sample in Table 3 showing "backface crazing," the defect was found to be a partial delamination. The supplier later informed us that this same defect had been observed in fabricating this series of specimens. The delamination phenomena was triggered by the rain erosion test in these specific specimens, but may not be a characteristic of producion quality lanthana-doped yttria.

OPTICAL SCATTER

Table 4 compares the total forward-integrated optical scatter of each sample measured before and after exposure to the rain field. Among the samples tested at UDRI, the only barely significant change occurred in Coors spinel, for which the average scatter at 0.647 µm increased from 6.2 to 6.8%. The near-infrared scatter of these same samples at 1.15 µm was not significantly changed. No other material tested at UDRI had any significant change in scatter. Among the samples from NADC, only lanthana-doped yttria had an increase of scatter (at both 0.647 and 1.15 µm wavelengths). However, all NADC samples had obviously not been handled carefully at NADC and required cleaning at NWC before scatter was measured after the rain erosion test. The increased scatter may be a result of mishandling, not rain erosion.

Scatter measured directly at a damage site of one TAF glass sample was greatly increased over the scatter of undamaged material. However, since the fraction of surface of any sample that was damaged is small, there is little change in average scatter for any material in any test.

CONCLUSIONS AND DISCUSSION

The principal conclusions are

1. ALON, Raytheon spinel, and sapphire survived these rain erosion tests with little damage.

2. Coors spinel, lanthana-doped yttria, and TAF glass were all damaged by these rain erosion conditions.

3. Optical scatter of unbroken samples is changed little or not at all by the rain erosion exposures of up to 40 minutes at 220 m/s (500 mi/h, Mach 0.64).

The samples used in these experiments are about twice as thick (5.1 mm) as a missile dome. Therefore, the absolute optical-scatter levels of undamaged samples are higher than what might be expected for missile domes. Since some scatter originates in the bulk material and some at the surface, reducing the thickness by a factor of two will not necessarily reduce scatter by a factor of two, because only the bulk contribution is halved.

The resistance to rain erosion that we observed in the present study is qualitatively consistent with that of a previous study whose results are displayed in Figure 11 (Reference 4). The data in the figure were derived from an experiment in which a 1.2-mm-diameter nylon bead was projected at each specimen at an impact angle of 30 degrees from perpendicular. The damage threshold is the speed at which surface damage first appeared. Consistent with the present study, sapphire, ALON, and Raytheon spinel have high-threshold velocities for impact damage, and lanthana-doped yttria has a lower-threshold velocity. Coors spinel withstood damage better in the previous tests than it did in our studies.

The hardness of ALON cited in Table 1 (1910 kg/mm^2) is based on manufacturer's data. We measured the Knoop hardness of one of the low-scatter Raytheon ALON disks after it survived rain erosion testing and found a value of 1482 ± 135 kg/mm^2 (Table 5, sample 27225).

This hardness is lower than the value in Table 1, but this disk demonstrated that it could survive the rain-erosion test with no damage. Subsequent to the rain-erosion tests, Raytheon modified its ALON production process to further reduce the scatter. Raytheon provided us with two thinner ALON disks with exceptionally low scatter, as shown in Table 5 (samples B-1 and C-1). The hardness of sample B-1 was essentially the same as that of sample 27255 that survived rain-erosion testing. The fracture toughness of sample B-1 was somewhat less than that of sample 27255. Taken together, the data suggest that the process used by Raytheon to decrease the scatter of ALON will not greatly reduce the rain erosion resistance below that of the samples we have tested.

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TABLE 1. Properties of Candidate Dome Materials Near Room Temperature.[a]

Properties	ALON	Spinel	La-doped yttria	Sapphire	MgF_2
Knoop hardness, kg mm^{-2}	19[illegible]0	1610 (Raytheon) 1400 (Coors)	730	2200	580
Flexural strength, MPa	300	190	210	400	100
Young's modulus, GPa	317	193	164	379	115
Poisson ratio	0.24	0.26	0.30	0.29	0.30
Thermal conductivity, W m^{-1} K^{-1}	13	15	5	24	12
Expansion coefficient, (10^{-6} K^{-1})(25-1000°C)	8	8	8	9	11
Density, g/mL	3.68	3.57	5.13	3.98	3.18
Heat capacity, J g^{-1} K^{-1}		0.92	0.48	0.90	
Melting point, K	2410	2410	2700	2310	1540
Thermal-shock figure of merit[b]	1.2	1.4	0.6	2.0	0.7
Refractive index at 4 μm	1.64	1.68	1.84	1.67	1.35

[a] Strength is strongly dependent on processing. Both strength and hardness depend on the method of measurement. Most properties in this table vary significantly with temperature.

[b] Thermal-shock figure of merit is defined as (strength)(1-ν)(k)/(αE), where ν is Poisson's ratio, k is thermal conductivity, α is the thermal expansion coefficient, and E is Young's modulus. Greater values of the thermal-shock figure of merit imply greater resistance to failure due to thermal shock. Units are (MPa)(W m^{-1} K^{-1})/(K^{-1})(GPa) = W/km.

TABLE 2. Forward Total Integrated Scatter of Rain Erosion Samples.

Material	Scatter, %[a]		
	0.647 μm	1.15 μm	3.39 μm
Samples for UDRI			
Crystal Systems sapphire	0.029 ± 0.012	0.019 ± 0.009	
Raytheon ALON[b]	1.9 ± 0.3	2.8 ± 0.2	1.05 ± 0.06
Raytheon high scatter ALON	17.8 ± 9.6	17.7 ± 8.8	
Raytheon spinel[c]	3.3 ± 1.0	2.0 ± 1.1	0.76 ± 0.37
Coors spinel	6.3 ± 1.3	3.7 ± 0.6	
GTE yttria[d]	4.0 ± 1.9	2.5 ± 1.2	0.94 ± 0.28
TAF glass	0.18 ± 0.16	0.12 ± 0.09	
Samples for NADC			
Crystal Systems Sapphire	0.020 ± 0.006	0.015 ± 0.004	...
Raytheon ALON	2.3 ± 1.1	3.0 ± 1.3	...
Raytheon Spinel	2.0 ± 0.2	0.88 ± 0.02	...
Coors Spinel	8.1 ± 3.0	4.9 ± 2.3	...
GTE Yttria	4.6 ± 0.1	3.0 ± 0.1	...
TAF glass	0.13 ± 0.04	0.086 ± 0.029	...

[a] Table gives average scatter (and standard deviation) for ten 5.1-mm-thick specimens of each material. Only five samples of Raytheon spinel for NADC test were available.

[b] Average transmission is 86.4% (± 0.8) at 0.647 μm and 87.4% (± 0.7) at 3.39 μm.

[c] Average transmission is 82.6% (± 1.4) at 0.647 μm, 85.6% (± 1.2) at 1.15 μm, and 88.5% (± 0.6) at 3.39 μm.

[d] Average transmission is 80.9% (± 1.0) at 0.647 μm, 82.0% (± 0.6) at 1.15 μm, and 81.9% (± 2.1) at 3.39 μm.

TABLE 3. Summary of Visual Damage in Rain Erosion Tests.

Material	UDRI		NADC	
	Time, min	Comments	Time, min	Comments
Sapphire (Crystal Systems)	20	No damage	20	No change
	20	No damage	20	No change
	20	No damage	25	No change
	20	No damage	25	No change
	25	Very slight pitting	30	No change
	25	Very slight pitting	30	No change
	30	Pitting	35	No change
	30	Pitting	35	No change
			40	No change
			40	No change
ALON (Raytheon)	10	No damage	20	No change
	10	No damage	20	No change
	20	No damage	25	No change
	20	No damage	25	No change
	30	No damage	30	No change
	30	No damage	30	No change
	40	No damage	35	No change
	40	No damage	35	No change
	40	No damage	40	No change
	40	No damage	40	No change
High-scatter ALON (Raytheon)	20	No damage		
	20	No damage		
	20	No damage		
	20	No damage		
	25	Slight pitting		
	25	Slight pitting		
	30	Pitting		
	30	Pitting		
Spinel (Raytheon)	5	No damage	20	No change
	5	No damage	25	No change
	10	No damage	30	No change
	10	No damage	35	No change
	15	No damage	40	No change
	15	No damage		
	20	No damage		
	20	No damage		
	40	No damage		
	40	No damage		

TABLE 3. (Contd.)

Material	UDRI		NADC	
	Time, min	Comments	Time, min	Comments
Spinel (Coors)	5	Very slight pitting, erosion damage	15	Surface pits
	5	Very slight pitting, erosion damage	15	Sample broke
	10	Slight pitting, erosion damage	20	Sample broke
	10	Slight pitting, erosion damage	20	No change
	15	Pitting, cratering, erosion damage	20	Small surface pits
	15	Pitting, cratering, erosion damage	25	Sample broke
	15	Pitting, cratering, erosion damage	25	Sample broke
	15	Pitting, erosion damage		
	20	Pitting, erosion damage		
	20	Pitting, erosion damage		
Lanthana-Doped Yttria (GTE)	5	No damage	10	Sample pitted, edge fractured
	5	No damage	10	Sample broke
	10	No damage	15	Sample broke
	10	No damage	15	Sample pitted, small edge fracture
	15	Slight pitting, 1 crater, erosion damage	20	Sample pitted, small edge fracture
	15	Slight pitting, erosion damage	20	Sample pitted, small edge fracture
	20	Pitting, backface crazing, erosion damage, 2 craters		
	20	Surface microcracks, pitting, backface crazing, erosion		
	40	Surface microcracks, pitting, erosion damage		
	40	Surface microcracks, pitting, backface crazing, erosion		

TABLE 3. (Contd.)

Material	UDRI		NADC	
	Time, min	Comments	Time, min	Comments
TAF-1 glass (Hoya) (Shaffer Omni Systems fabrication)	5	Slight pitting, erosion damage	10	Sample broke
	5	Slight pitting, erosion damage	10	Surface eroded, edge chipped & cracked
	5	Pitting, erosion damage	15	Surface eroded, edge chipped
	5	Pitting, erosion damage	15	Sample broke
	7.7	Pitting, erosion damage	20	Sample broke
	7.7	Specimen fractured at 2 min	20	Sample broke
	20	Pitting, surface microcracks, erosion damage, cratering		
	20	Pitting, surface microcracks, erosion damage, cratering		

TABLE 4. Forward Total Integrated Scatter Measured Before and After Rain Erosion Tests.

		647 μm		1.15 μm		3.39 μm	
Time, min	Comments	Before	After	Before	After	Before	After
Sapphire (Crystal Systems)							
UDRI							
20	No damage	0.019%	0.020%	0.012%	0.023%	...	...
20	No damage	0.043	0.020	0.029	0.024	...	...
20	No damage	0.031	0.012	0.015	0.016	...	...
20	No damage	0.016	0.018	0.010	0.021	...	...
25	Very slight pitting	0.038	0.055	0.028	0.038	...	...
25	Very slight pitting	0.048	0.026	0.035	0.032	...	...
30	Pitting	0.016	0.072	0.011	0.051	...	...
30	Pitting	0.037	0.015	0.027	0.021	...	...
Average change of scatter		-0.001		+0.007			
NADC							
20	No change						
20	No change	Individual changes in scatter are not known					
25	No change						
25	No change	At 0.647 μm					
30	No change	Average scatter before test = 0.020 ± 0.006%					
30	No change	Average scatter after test = 0.016 ± 0.008%					
35	No change						
35	No change	At 1.15 μm					
40	No change	Average scatter before test = 0.015 ± 0.004%					
40	No change	Average scatter after test = 0.015 ± 0.004%					
ALON (Raytheon)							
UDRI							
10	No damage	1.7%	1.7%	2.6%	...	1.0%	0.9%
10	No damage	2.1	2.2	3.0	...	1.1	1.0
20	No damage	2.2	2.2	3.1	...	1.1	1.0
20	No damage	2.0	1.9	2.9	...	1.1	1.0
30	No damage	2.0	1.8	2.9	...	1.0	1.0
30	No damage	2.1	1.8	3.1	...	1.1	1.0
40	No damage	1.6	1.6	2.7	...	1.0	0.9
40	No damage	1.5	1.6	2.5	...	1.0	0.9
40	No damage	1.7	1.8	2.7	...	1.0	0.9
40	No damage	1.6	2.0	2.8	...	1.1	1.0
Average change of scatter		0.0				-0.1	

TABLE 4. (Contd.)

Time, min	Comments	647 μm		1.15 μm		3.39 μm	
		Before	After	Before	After	Before	After
ALON (Raytheon)							
NADC							
20	No change	0.7%	0.5%	1.1%	1.2%	...	...
20	No change	3.1	2.6	4.1	4.5	...	...
25	No change	0.8	0.5	1.1	1.1	...	...
25	No change	2.2	1.7	2.9	3.2	...	...
30	No change	3.3	2.8	4.1	4.3	...	...
30	No change	3.2	2.8	4.2	4.6	...	...
35	No change	2.9	2.4	3.8	4.2	...	...
35	No change	2.5	1.6	2.9	3.1	...	...
40	No change	3.3	2.4	4.1	4.2	...	...
40	No change	0.9	0.5	1.3	1.4	...	...
Average change of scatter		-0.5		+0.2			
High-Scatter ALON (Raytheon)							
UDRI							
20	No damage	23.8%	22.8%	23.0%	23.2%	...	...
20	No damage	4.7	4.0	5.6	5.8	...	...
20	No damage	4.2	4.2	5.4	5.6	...	...
20	No damage	27.0	28.3	27.1	27.9	...	...
25	Slight pitting	22.7	22.9	21.7	22.5	...	...
25	Slight pitting	25.1	25.5	24.2	25.0	...	...
30	Pitting	26.3	27.3	25.9	26.9	...	...
30	Pitting	21.1	21.2	20.5	20.8	...	...
Average change of scatter		+0.2		+0.5			
Spinel (Raytheon)							
UDRI							
5	No damage	3.1%	3.6%	1.7%	...	0.7%	0.7%
10	No damage	2.5	2.9	2.7	...	0.6	0.6
10	No damage	3.8	4.2	1.2	...	1.0	1.0
15	No damage	2.6	2.8	1.4	...	0.5	0.5
15	No damage	3.4	3.2	1.7	...	0.6	0.6
20	No damage	2.8	2.8	1.3	...	0.6	0.6
20	No damage	2.7	2.9	1.5	...	0.6	0.6
40	No damage	3.3	3.3	1.8	...	0.7	0.7
40	No damage	2.6	2.8	1.3	...	0.6	0.6
Average change of scatter		+0.3				0.0	
NADC							
20	No change	1.8%	1.8%	0.9%	0.9%	...	...
25	No change	2.1	2.1	0.9	0.9	...	...
30	No change	2.2	2.2	0.9	0.9	...	...
35	No change	2.1	2.3	0.9	1.0	...	...
40	No change	2.0	2.1	0.9	0.9	...	...
Average change of scatter		+0.1		0.0			

TABLE 4. (Contd.)

		647 µm		1.15 µm		3.39 µm	
Time, min	Comments	Before	After	Before	After	Before	After
		Spinel (Coors)					
UDRI							
5	Very slight pitting, erosion damage	7.5%	7.9%	3.8%	3.8%	. . .	. . .
5	Very slight pitting, erosion damage	6.2	7.0	3.3	3.6	. . .	. . .
10	Slight pitting, erosion damage	4.8	5.2	3.3	3.4	. . .	. . .
10	Slight pitting, erosion damage	8.0	8.9	4.5	4.7	. . .	. .
15	Pitting, cratering, erosion damage	4.5	5.8	3.4	3.6	. . .	. . .
15	Pitting, cratering, erosion damage	7.9	7.9	4.5	4.4	. . .	. . .
15	Pitting, cratering, erosion damage	7.0	7.7	4.0	4.2	. . .	. . .
15	Pitting, erosion damage	6.5	7.4	4.0	4.1	. . .	. . .
20	Pitting, erosion damage	4.9	5.2	2.4	2.5	. . .	. . .
20	Pitting, erosion damage	5.2	5.4	3.4	3.4	. . .	. . .
Average change of scatter		+0.6		0.1			
NADC							
15	Surface pits	6.6%	6.8%	3.6%	3.8%	. . .	. . .
15	Sample broke	5.4	. . .	3.8	. . .	. . .	. . .
20	Sample broke	11.9	. . .	7.5	. . .	. . .	. . .
20	No change	6.8	6.8	3.8	3.7	. . .	. . .
20	Small surface pits	7.0	6.9	4.1	3.9	. . .	. . .
25	Sample broke	14.2	. . .	9.9	. . .	. . .	. . .
25	Sample broke	7.0	. . .	4.1	. . .	. . .	. . .
Average change of scatter		0.0		0.0			

TABLE 4. (Contd.)

		647 μm		1.15 μm		3.39 μm	
Time, min	Comments	Before	After	Before	After	Before	After
		Lanthana-Doped Yttria (GTE)					
UDRI							
5	No damage	2.3%	2.4%	1.4%	...	0.7%	0.6%
5	No damage	2.2	2.5	1.4	...	0.8	0.8
10	No damage	6.9	7.0	3.9	...	1.0	1.2
10	No damage	4.7	5.0	2.8	...	0.9	1.0
15	Slight pitting, 1 crater, erosion damage	3.1	3.4	1.6	...	0.9	1.0
15	Slight pitting, erosion damage	2.5	3.0	1.6	...	0.9	0.9
20	Pitting, backface crazing, erosion damage, 2 craters	6.4	6.8	3.9	...	1.1	1.2
20	Surface microcracks, pitting, backface crazing, erosion	2.6	2.9	1.5	...	0.8	0.8
40	Surface microcracks, pitting, erosion damage	3.4	3.8	2.0	...	0.7	1.1
40	Surface microcracks, pitting, backface crazing, erosion	6.3	6.4	4.5	...	1.6	2.0
Average change of scatter		+0.3				+0.1	
NADC							
10	Sample pitted, edge fractured	4.3%	5.4%	2.8%	3.8%	...	...
10	Sample broke	4.6	...	3.1	...	...	...
15	Sample broke	4.6	...	3.0	...	...	...
15	Sample pitted, small edge fracture	4.5	5.3	3.0	3.8	...	...
20	Sample pitted, small edge fracture	4.7	5.8	3.0	4.1	...	...
20	Sample pitted, small edge fracture	4.7	6.0	3.3	4.5	...	...
Average change of scatter		+0.8		+1.0			

TABLE 4. (Contd.)

Time, min	Comments	647 µm Before	647 µm After	1.15 µm Before	1.15 µm After	3.39 µm Before	3.39 µm After
TAF-1 Glass (Hoya) (Shaffer Omni Systems Fabrication)							
UDRI							
5	Slight pitting, erosion damage	0.08%	0.10%	0.09%	0.09%	...	...
5	Slight pitting, erosion damage	0.47	0.17	0.26	0.16	...	...
5	Pitting, erosion damage	0.20	0.22	0.18	0.18	...	...
5	Pitting, erosion damage	0.47	0.11	0.30	0.12	...	...
7.7	Pitting, erosion damage	0.07	0.08	0.04	0.69	...	...
7.7	Specimen fractured at 2 min	0.04	...	0.05	...	...	...
20	Pitting, surface microcracks erosion damage, cratering	0.08	0.31	0.05	0.21	...	...
20	Pitting, surface microcracks erosion damage, cratering	0.14	0.61	0.08	0.43	...	...
Average change of scatter		+0.01		+0.13			
NADC							
10	Sample broke	0.06%	...	0.04%	...	...	...
10	Surface eroded, edge chipped & cracked	0.12	...	0.06	...	...	...
15	Surface eroded, edge chipped	0.11	...	0.08	...	...	...
15	Sample broke	0.10	...	0.08	...	...	...
20	Sample broke	0.18	...	0.13	...	...	...
20	Sample broke	0.13	...	0.10	...	...	...

TABLE 5. Comparison of Raytheon ALON Specimens.

Sample	Thickness, mm	Forward total integrated scatter 0.647 μm	Forward total integrated scatter 3.39 μm	Knoop hardness, kg/mm^2	Fracture toughness $MPa\sqrt{m}$
27225[a]	5.1	1.72 ± 0.06%	0.97 ± 0.3%	1482 ± 135[b]	1.49 ± 0.20[c]
B-1	2.0	0.25 ± 0.02%	0.05 ± 0.02%	1499 ± 114[d]	1.20 ± 0.10[c]
C-1	2.0	0.14 ± 0.02%	0.06 ± 0.02%	...	...

[a] Sample 27225 survived 10 min in the UDRI rain field.
[b] 31 measurements, 300-g load.
[c] 5 measurements, 300-g load.
[d] 17 measurements, 300-g load.

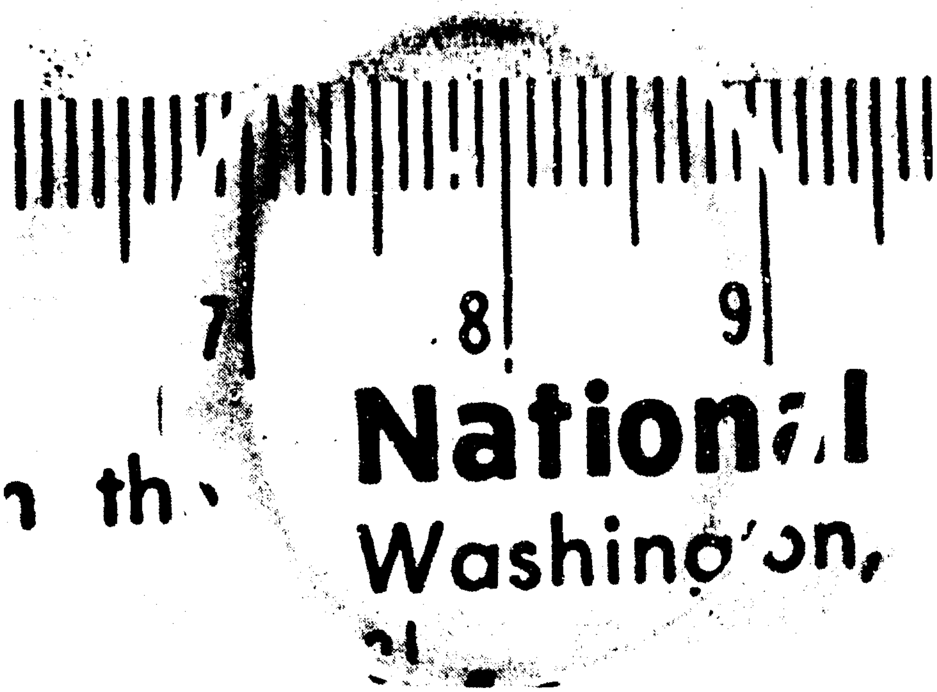

FIGURE 1. Coors Spinel Specimen No. 7 Run at NADC for 15 min.

FIGURE 2. Photomicrograph of Largest Flaw on Disk in Figure 1 Taken in Transmitted Light Between Crossed Polarizers at 100x.

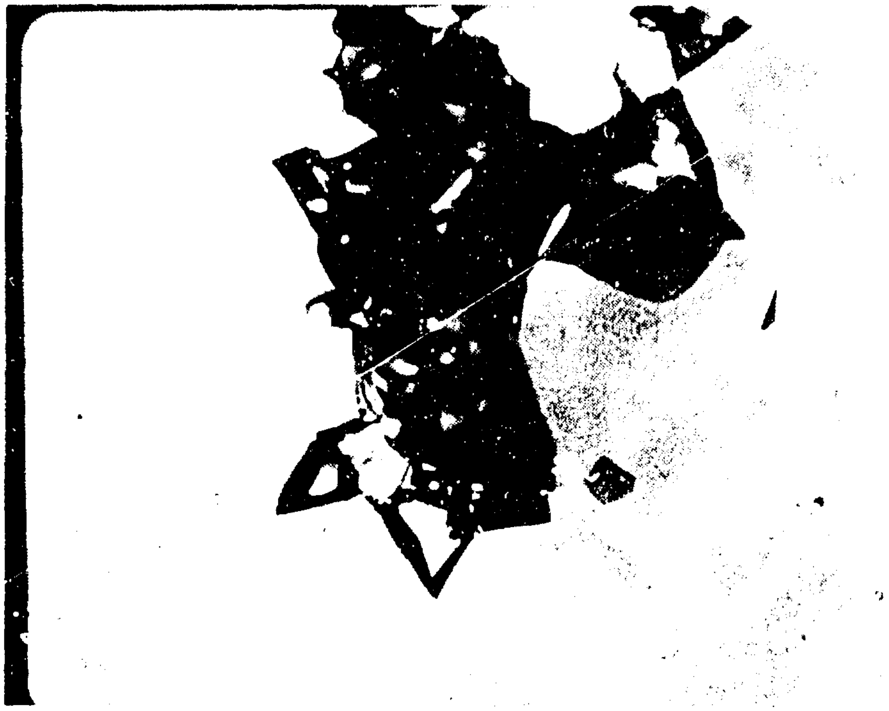

FIGURE 3. Photomicrograph of Flaw in Center of Disk in Figure 1 Taken in Transmitted Light Between Crossed Polarizers at 100x.

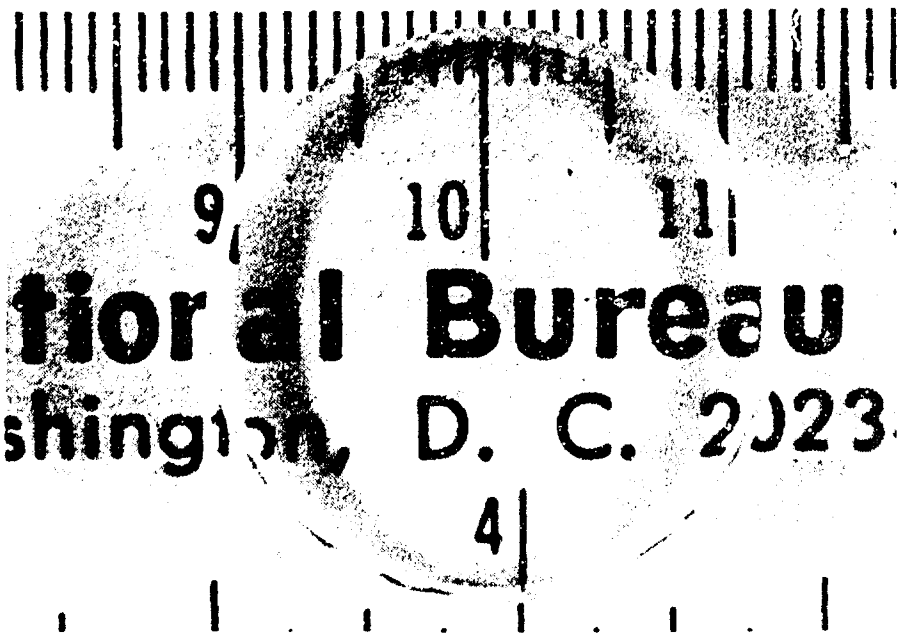

FIGURE 4. Coors Spinel Specimen No. 24362 Run at UDRI for 20 min.

FIGURE 5. Photomicrograph of Flaw on Disk in Figure 4 Taken in Reflected Nomarski (Differential Interference Contrast) at 200x.

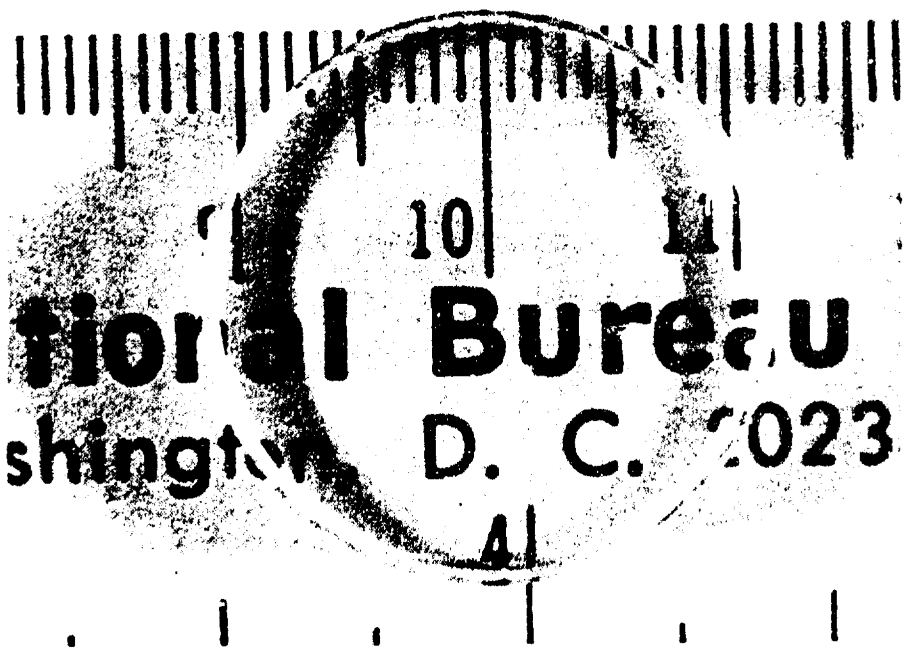

FIGURE 6. Photograph of Sapphire Specimen No. 24345 Run at UDRI for 30 min.

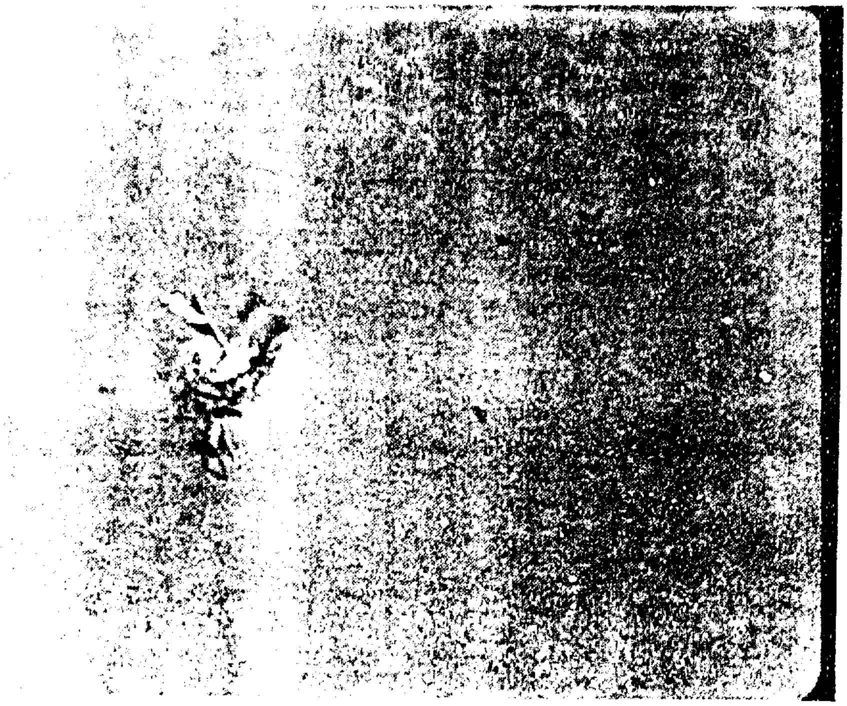

FIGURE 7. Photomicrograph of a Flaw on Sapphire Specimen No. 24343 Run at UDRI for 25 min. Micrograph was taken in reflected Nomarski (differential interference contrast) at 160x.

FIGURE 8. Photomicrograph of a Flaw on Raytheon High-Scatter ALON Specimen No. 24353 Run at UDRI for 25 min. Micrograph was taken in reflected Nomarski (differential interference contrast) at 160x.

FIGURE 9. Photomicrograph of Damage on GTE Lanthana-Doped Yttria Specimen No. 27242 Run at UDRI for 20 min. Micrograph was taken in reflected Nomarski (differential interference contrast) at 160x.

FIGURE 10. Photomicrograph of Damage on GTE Lanthana-Doped Yttria Specimen No. 27242 Run at UDRI for 20 min. Micrograph was taken in reflected Nomarski (differential interference contrast) at 160x.

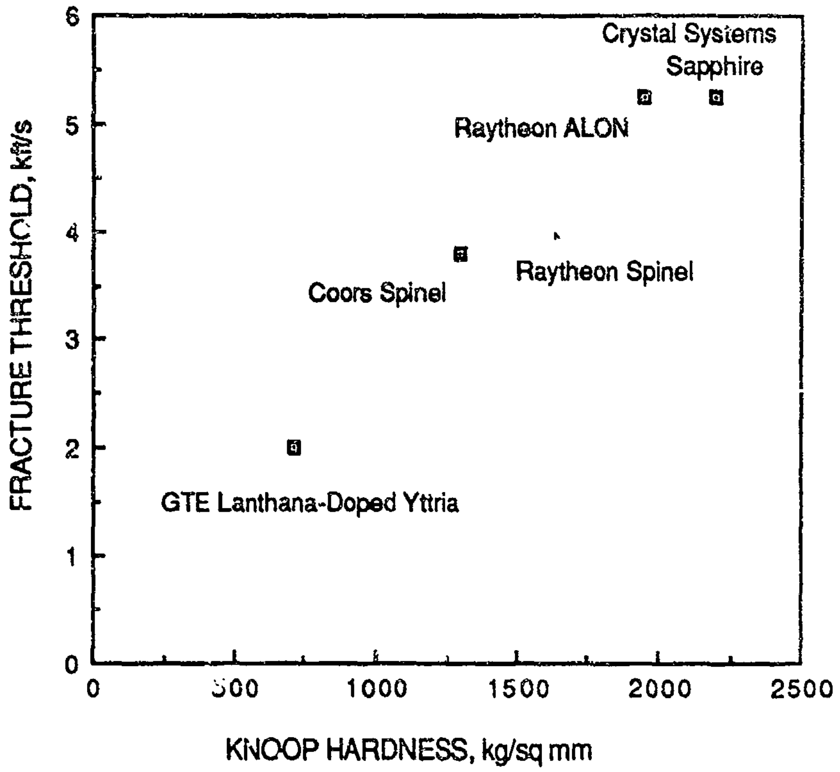

FIGURE 11. FractureThreshold for Damage by 1.2-mm-Diameter Nylon Bead as a Function of Material Hardness (Reference 4).

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Linda G. Hall
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